

ACTIVATION ENERGY AND CAPTURE CROSS SECTION OF
MAJORITY CARRIER TRAPS IN Zn DOPED InP

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Schottky barrier diodes were fabricated on Zn doped InP Wafers. The diodes were radiation damaged with 2 MeV protons to a dose of $2 \times 10^{12} \text{cm}^{-2}$. The damage was analyzed by DLTS (deep level transient spectroscopy) using the double correlation technique. Capture cross sections were measured directly. Two major defects were observed in the DLTS spectra. The first defect, was H4 at $E_v + 0.29 \text{ eV}$, with capture cross section $1.1 \times 10^{-17} \text{cm}^2$. The second defect, was H5 at $E_v + 0.53 \text{ eV}$. Its capture cross section varied with temperature as described by the relationship $\sigma = \sigma_0 \exp^{-E/kT}$ where $\sigma_0 = 1.3 \times 10^{-19} \text{cm}^2$ and $\Delta E = .08 \text{ eV}$. This relationship yields a σ of $5.9 \times 10^{-21} \text{cm}^2$ at room temperature. The surprisingly small capture cross section of H5 and its temperature dependence are discussed in terms of the multiphonon emission process for carrier capture at the defect. The advantages of the improved experimental techniques used are also discussed.

INTRODUCTION

Deep Level Transient Spectroscopy (DLTS) has been widely used in studies of electrically active defects in semiconductors. A DLTS analysis can tell whether a defect is a majority or minority carrier trap, the defect energy level, its capture cross section and the trap concentration. However DLTS has some limitations. A suitable diode sample is required for the analysis. High quality ohmic and or Schottky contacts are required. The sample must be of limited capacitance and low resistance (1), the junction or barrier must have very small leakage current (2), and the concentration of electrically active defects must be limited (3).

A DLTS analysis is performed using a diode sample, pulse generator, DC power supply and capacitance meter. The sample is reverse biased to deplete the region below the contact of carriers. A pulse generator is used to inject carriers into the depletion region. At the end of the injection pulse the sample capacitance returns to its quiescent value rapidly if no traps are present. If there are traps in the depletion region, they will capture carriers during the injection pulse and then emit the trapped carriers in a thermally activated process at its end. This causes a slow return to the quiescent capacitance or a capacitance transient. The analysis of this transient yields the defect parameters.

The magnitude of the capacitance transient is related to the charge trapped and thus the concentration of the defect. The following relationship was derived by Lang (4).

$$N_t / N_d = 2 \Delta C / C_0 ,$$

where N_t is the trap concentration, N_d is the doping concentration, C_0 is the quiescent capacitance and ΔC is the magnitude of the capacitance transient.

The carriers trapped at the defect are thermally excited from the defect level. The emission rate of carriers is described by the following relation (4).

$$\epsilon = (\sigma v N/g) \exp^{-E/kT},$$

where ϵ is the emission rate, σ is the capture cross section, N is the density of states, v is the thermal velocity, g is the degeneracy of the level, E is the activation energy, k is Boltzmann's constant and T the absolute temperature.

The capacitance transient decays exponentially as the carriers are emitted, and the time constant of the decay is analyzed to determine the trap parameters. The transient is normally monitored by correlators which respond to the time constant with which the transient decays. The analysis is carried out by varying the temperature from liquid nitrogen or helium temperature to room temperature with 3 or more different correlator time constants. This allows the fixing of an emission rate and temperature at which it is occurring. A plot of $\ln \epsilon / T^2$ versus $1/T$ has a slope of E/k and from the intercept the apparent capture cross section can be extracted.

The speed, sensitivity and simplicity of DLTS have led to its application to a large number of systems. A large number of DLTS articles are available in the literature. Unfortunately many of the results may have been compromised by poor technique and by some of the intrinsic assumptions made in the analysis.

The limitations of the technique are associated with the characteristics of the depletion region near the contacts. Figure 1 shows the depletion region in the area below the contact. The conduction band and valence bands, Fermi level and defect levels are shown. It is apparent that the occupancy of some of the traps cannot be changed. These traps will always be above the Fermi level due to the band bending. The deeper the trap the larger the fraction of traps affected. A correction must be applied to the defect concentration calculation or the trap concentration will not be accurately measured (5).

A second effect involves the carrier concentration near the edge of the depletion region. Near the edge of the depletion region band bending results in a carrier concentration that varies and is less than that in the bulk. The change in carrier concentration affects the carrier capture properties in that region. This phenomenon is called the Debye tail effect (6). The strong electric field near the junction may also affect capture and emission (7). The electric field is a maximum at the contact or junction. The high field may result in tunneling of carriers out of deep levels in addition to the expected thermally activated emission. The magnitude of the field varies across the depletion region and may cause a variation in emission rates across the depletion region. Both of these phenomena may result in non-exponential capacitance transients.

The above mentioned complications may affect both the measured activation energy of a defect and its apparent capture cross section. The method of estimating the capture cross section from the intercept of an activation energy plot can be compromised if the capture cross section varies with temperature, and the values thus obtained should be treated with caution unless verified by direct measurements.

A direct measurement of the capture cross section can be made by varying the injection pulse width at a fixed temperature during a DLTS measurement (8). A plot of the variation of the magnitude of the capacitance transient versus injection pulse width will have a slope equal to

$$M = \sigma v N_d,$$

where M is the slope, σ is the capture cross section, v is the thermal velocity of the carriers and N_d is the dopant concentration. A plot of $\ln M$ versus $1/T$ will reveal the true capture cross section and, if measurements are made over a range of temperatures, any activation energy associated with it.

Both activation energy and capture cross section measurements can be influenced by non-exponentiality in carrier capture and emission phenomena. In most cases this is associated with the extremes of the depletion region. These regions can be avoided by using Double Correlation Deep Level Transient Spectroscopy (DDLTS) (9). In DDLTS two pulse generators are used to generate two fill pulses

of different magnitudes, but neither completely collapses the depletion region. The transients are analyzed using two correlators whose outputs are subtracted. The resulting signal is due only to traps in the center of the depletion region. This technique thus avoids the Debye tail region and minimizes the effect of a varying electric field across the depletion region. In the present case the improved DDLTS technique was used to study proton radiation damage in p-type Zn doped InP.

EXPERIMENTAL

Schottky barrier diodes were fabricated on Zn doped p-type Inp wafers. The wafers were grown by the CZ process and had a carrier concentration of $2.5 \times 10^{16} \text{cm}^{-3}$. Contacts were electron beam evaporated, Au for the Schottky contact and Au-Zn alloy with a subsequent heat treatment for the ohmic contact. The diodes were characterized by IV, CV and DLTS; no traps were present in the as processed diodes. The diodes were radiation damaged, at room temperature, using 2 MeV protons to a dose of $2 \times 10^{12} \text{cm}^{-3}$. Current was limited to 2 nA to limit sample heating. The diodes were then analyzed by CV, DLTS and DDLTS techniques. DLTS spectra were taken at -4 volt bias with a 4 volt fill pulse. DDLTS spectra were taken at -6 volt bias with 2 volt and 4 volt fill pulses. The values obtained for trap concentration, activation energy and capture cross sections are contained in Table 1.

RESULTS

Analysis of the diodes after radiation revealed significant carrier loss. Before radiation the mean carrier concentration was $N_d = 2.6 \times 10^{16} \text{cm}^{-3}$, post radiation carrier concentration was $N_d = 1.3 \times 10^{16} \text{cm}^{-3}$. The loss was then $1.3 \times 10^{16} \text{cm}^{-3}$ or 6500cm^{-1} . This result falls somewhere between that for 500 KeV protons, 8400cm^{-1} , and 3 MeV protons, 1400cm^{-1} , as reported by Weinberg et al (10). The values however, must be compared carefully, due to the different diode structures used in the experiments.

Figure 2 is a typical spectrum taken during DLTS analysis. Spectra obtained during both DLTS and DDLTS were analyzed and the data appears in Table 1. Two traps were present in the spectra. The peak appearing at lower temperature had an activation energy of $E_v + 0.33 \text{ eV}$ as determined by DLTS and $E_v + 0.29 \text{ eV}$ as determined by DDLTS. This energy level is consistent with the trap H4 at $E_v + 0.37 \text{ eV}$, as obtained by standard DLTS, in the literature (11). The defect H4 was present at an average concentration of $4.5 \times 10^{14} \text{cm}^{-3}$ as determined by DDLTS.

The apparent capture cross section of the defect H4 has been reported to be $8 \times 10^{-16} \text{cm}^2$ as determined by the intercept method. The capture cross section determined from the activation energy plot intercept was $6.3 \times 10^{-16} \text{cm}^2$ using DLTS and $1.1 \times 10^{-16} \text{cm}^2$ using DDLTS. The data however varied considerably from sample to sample and much more so than the activation energies.

Direct measurements of the capture cross section of H4 were not attempted previously due to the limited pulse width generation ability of most DLTS equipment (12,13). This limitation has been overcome in this case by interfacing a high speed external pulse generator to the DLTS equipment. Pulses as narrow as 50 nS could be generated by this method. Using this technique the majority carrier capture cross section of the defect H4 was directly measured to be $1.1 \times 10^{-17} \text{cm}^2$. Capture cross section measurements made at various temperatures showed the capture cross section of H4 to be independent of temperature, as shown by Figure 3.

The peak appearing at higher temperatures in the DLTS spectra was determined to have an energy level at $E_v + 0.60 \text{ eV}$ by DLTS and $E_v + 0.53 \text{ eV}$ by DDLTS. This level is consistent with the defect H5 at $E_v + 0.52 \text{ eV}$ as reported in the literature (11). The defect H5 was present at an average concentration of $3.3 \times 10^{14} \text{cm}^{-3}$.

The apparent capture cross section of the defect H5 has been reported to be $5.5 \times 10^{-15} \text{cm}^2$ (11). The capture cross sections determined by the intercept method were $8.5 \times 10^{-14} \text{cm}^2$ using DLTS and $1.6 \times 10^{-14} \text{cm}^2$ using DDLTS, both with significant variation from sample to sample.

Direct measurements of the capture cross section of H5 have been performed. These measurements differ widely from the apparent cross section. Bretagnon et al have measured a thermally activated majority carrier capture cross section described by the relation

$$\sigma = \sigma_0 \exp^{-\Delta E_0/kT}$$

with $\sigma_0 = 1 \times 10^{-13} \text{cm}^2$ and $\Delta E_0 = 0.27 \text{ eV}$, where σ_0 is the intercept of the $\ln \sigma$ vs $1/T$ plot and ΔE_0 is the activation energy associated with the capture cross section (13). Walters and Summers found a similar temperature dependence with $\Delta E_0 = 0.13 \text{ eV}$ (14). In the present work the capture cross section of H5 was found to be temperature dependent, as seen in Figure 3, with $\sigma_0 = 1.3 \times 10^{-19} \text{cm}^2$ and $\Delta E = 0.08 \text{ eV}$.

DISCUSSION

The defect H4 has been suggested to be a primary defect occurring in the P sublattice of InP. These observations were made after demonstrating an anisotropy in the defect introduction rate when radiation damage was introduced in the crystal along a direction favoring P displacement (15). The activation energy measured by DLTS is in reasonable agreement with the literature value. The value measured by DDLTS is somewhat less. The difference is due to the more favorable carrier capture and emission observed in the center of the depletion region, an advantage of the DDLTS technique.

The directly measured capture cross section was substantially less than the value obtained the intercept method, but in other systems the directly measured values are often an order of magnitude less than those from the intercept method (16).

The defect H5 has been suggested to be a complex of a simple defect and a doping atom, due to the dependence of its observed concentration on the doping level (17). The activation energy of H5 as determined by DLTS is in good agreement with the literature value, the value obtained by DDLTS is again somewhat less. The value obtained by DDLTS is different because is obtained only from traps favorably situated in the center of the depletion region.

The activation energy associated with capture is the cause of the difference between the values of H5 from the indirect intercept technique and direct measurements. The intercept method assumes a capture cross section independent of temperature. The value of σ_0 obtained from the activation energy plot intercept, $5.5 \times 10^{-15} \text{cm}^2$ is vastly different from the intercept of the plot of the $\ln \sigma$, the directly measured values vs $1/T$, $1.3 \times 10^{-19} \text{cm}^2$. In addition, the activation energy associated with capture reduces the capture cross section to $5.9 \times 10^{-21} \text{cm}^2$ at room temperature. Use of the value obtained by the indirect method would lead to an error of six orders of magnitude!

An activation energy associated with capture cross section may also cause errors in the measurement of the trap energy level. The activation energy for capture must be subtracted from the ΔE value obtained for the trap level. The resultant trap level for H5 is $E_v + 0.45 \text{ eV}$.

The difference in the present results of direct measurements of the capture cross section and those of previous authors are a result of limitations associated with the measurement technique. The trap H5 at $E_v + 0.53 \text{ eV}$ is a very deep trap. When attempting to measure the capture cross section of H5 in DLTS a significant region near the contact is affected by the Debye tail effect. Traps near the interface will not be able to capture carriers during the measurement period, or will fill at a rate different than those in the bulk. This can produce a non-exponential transient. These effects are more significant for a deeper traps like H5. In this work the surface region was avoided by measuring the capture cross section of H5 by pulse width variation technique using DDLTS. With this technique capture and emission are more ideally exponential and better values for the extracted parameters are obtained.

The value obtained for the capture cross section of H4 is consistent with the size of a simple atomic defect or πr^2 where r is an atomic radius or 10^9 cm . The small value for the capture cross section of H5

and the variation of cross section with temperature shows that carrier capture at H5 is obviously more complicated than at a simple defect.

Henry and Lang have observed small values of capture cross section that vary with temperature in GaP and GaAs and developed the multiphonon emission model (MPE) to explain the results (18). In the multiphonon emission model it is theorized that a large lattice relaxation is associated with capture of a carrier at the defect. This relaxation and the subsequent shift of the defect and energy band minima gives rise to a barrier associated with capture of a carrier at a defect, as shown schematically in Figure 4. The temperature dependence of the capture cross section is related exponentially to this barrier.

$$\sigma = \sigma_0 \exp^{-E_a/kT}$$

The presence of the activation energy barrier reduces the capture cross section below that which would be expected for a simple trap. The energy associated with the capture causes a violent lattice vibration at the defect and is emitted as phonons into the lattice during the damping of this vibration; this feature gives the model its name. This violent lattice vibration may cause defect motion or recombination enhanced defect reactions. These reactions have been observed in InP, GaAs and GaP (19,20).

CONCLUSIONS

By using the DDLTS technique improvements in the measured values of activation energy and capture cross section can be realized. The values for the activation energy of H4 and H5 obtained by DDLTS were less than those obtained by DLTS but in reasonable agreement with the literature values. The DDLTS method is preferable as it minimizes the effect of the Debye tail and junction electric field. The values obtained for capture cross sections however were not in good agreement with the literature. This was partially due to the fact that few direct measurements of cross sections are made and in many studies apparent cross sections are reported. The assumption that the actual capture cross section of a defect is equal to the apparent capture cross section, determined by the intercept of an activation energy plot, is not generally valid. An activation energy associated with capture may cause the capture cross section to be very much different. In addition the activation energy associated with capture cross section must be applied to the activation energy for trap emission or the reported defect energy level will be in error. Direct measurements of capture cross section also displayed much less variation from sample to sample than values from the intercept method. The values of capture cross section for the trap H5 were much smaller than those for the trap H4 and varied with temperature. The properties of the trap H5 are consistent with carrier capture by multiphonon emission.

REFERENCES

1. A.Broniatowski, A.Blosse, P.Srivasta and J.Bourgoin.,J.Appl.Phys.,54,2907(1983)
2. M.Chen, D.Lang, W.Smith, A.Sergent, J.Harbison, Appl.Phys.Lett.,44,790(1984)
3. D.Stievenaard, M.Lannoo and J.C.Bourgoin, Solid State Elec.,28,482(1985)
4. D.Lang, J.Appl.Phys.,45,3023(1974)
5. J.Bourgoin and M.Lannoo, Point Defects in Semiconductors II, Springer-Verlag, NY, NY, (1983)p.167.
6. Y.Zohta and M.Watanabe, J.Appl.Phys.,53,1809(1982)
7. G.Vincent, A.Chantre and D.Bois, J.Appl.Phys.,50,5484(1979)
8. A.Telia, B.Lepely and C.Michel, J.Appl.Phys.,69,7159(1991)
9. H.Lefevre and M.Schulz, Appl.Phys.,12,45(1977)
10. I.Weinberg, Proc. XII Space Photovoltaic Research And Technology Conf.,Cleveland,Ohio,1992
11. I.Weinberg, Solar Cells,31,331(1991)
12. M.Levinson, H.Tempkin and W.Bonner, J.Elec.Mater.,12,423(1983)
13. T.Bretagnon, G.Bastide and M.Rouzeyre, Phys.Rev.B.41,1028(1990)
14. R.Walters and G.Summers, J.Appl.Phys.,69,6491(1991)
15. A.Sibile, J.Suski and G. Le Roux, Phys.Rev.B.,30,1119(1984)
16. Lang, Ann.Rev.Mater.Sci.,377(1977)
17. M.Yamaguchi and K.Ando, J.Appl.Phys.,60,935(1986)
18. C.Henry and D.Lang, Phys.Rev.B,15,989(1977)
19. D.Lang and L.Kimmerling, Phys.Rev.Lett.,33,489(1974)
20. K.Ando, M.Yamaguchi and C.Umera, Phys.Rev.B,34,3041(1986)

TRAP	Nt cm^{-3}	DLTS ΔE eV	σ_a cm^2	DDLTS ΔE eV	σ_a cm^2	σ_d cm^2	ΔE_σ eV
H4	4.5×10^{14} ± 0.45	0.33 ± 0.04	6.3×10^{-16} $\pm 7 \times 10^{-16}$	0.29 ± 0.03	1.1×10^{-16} $\pm 2 \times 10^{-18}$	1.1×10^{-17} $\pm 3 \times 10^{-18}$	0
Lit.		0.37	8×10^{-16}				
H5	3.3×10^{14} ± 0.98	0.60 ± 0.03	8.5×10^{-14} $\pm 9 \times 10^{-14}$	0.53 ± 0.05	1.6×10^{-14} $\pm 2 \times 10^{-14}$	1.3×10^{-19} $\pm 2 \times 10^{-20}$.08 ± 0.01
Lit.		0.52	5.5×10^{-15}				

Table I: Summary of DLTS, DDLTS, and Capture Cross Section Measurements, σ_a is the apparent cross section and σ_d is the directly measured cross section.

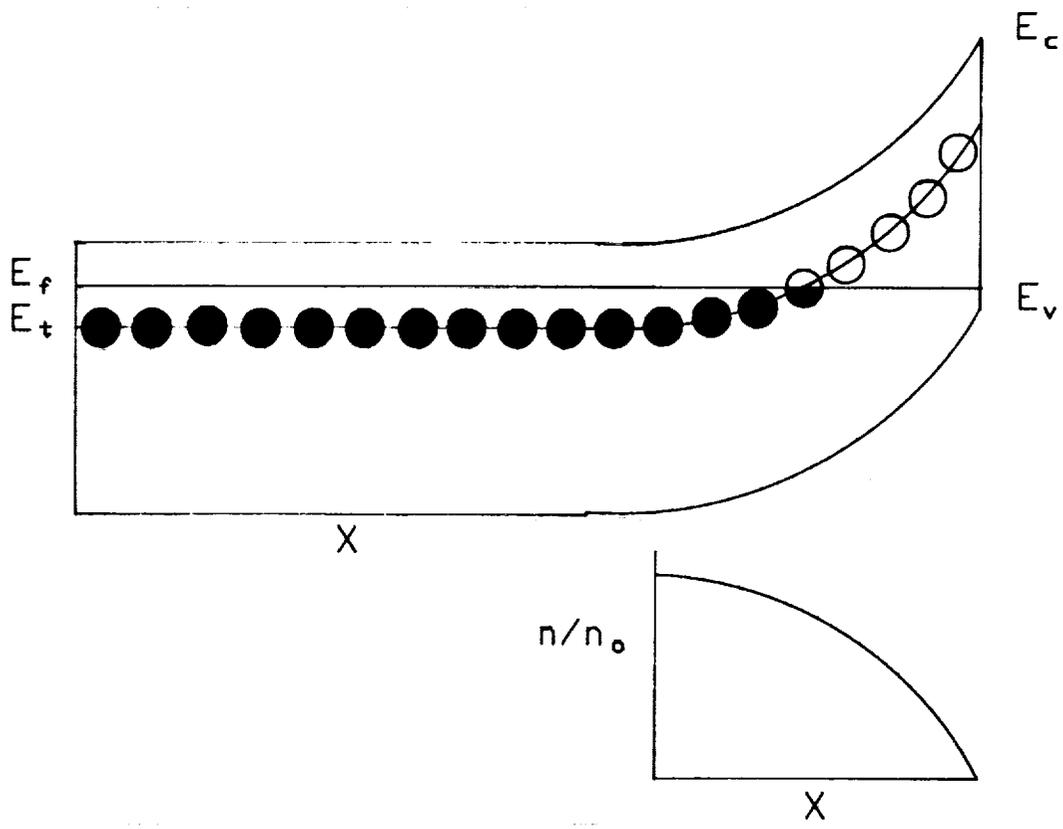
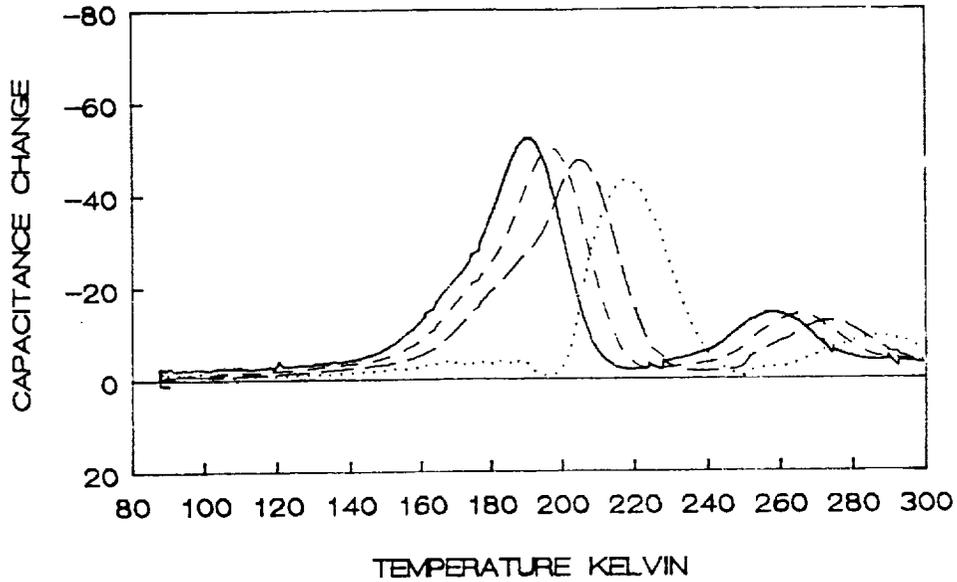


FIGURE 1: DEPLETION REGION AND DEBYE TAIL EFFECT

PROTON DAMAGED InP DLTS SPECTRUM

——— 43 mS - - - 21.5 m - - - 8.6 mS 2.1 mS



TRAP LEVELS IN InP

—△— H4 -△- H5

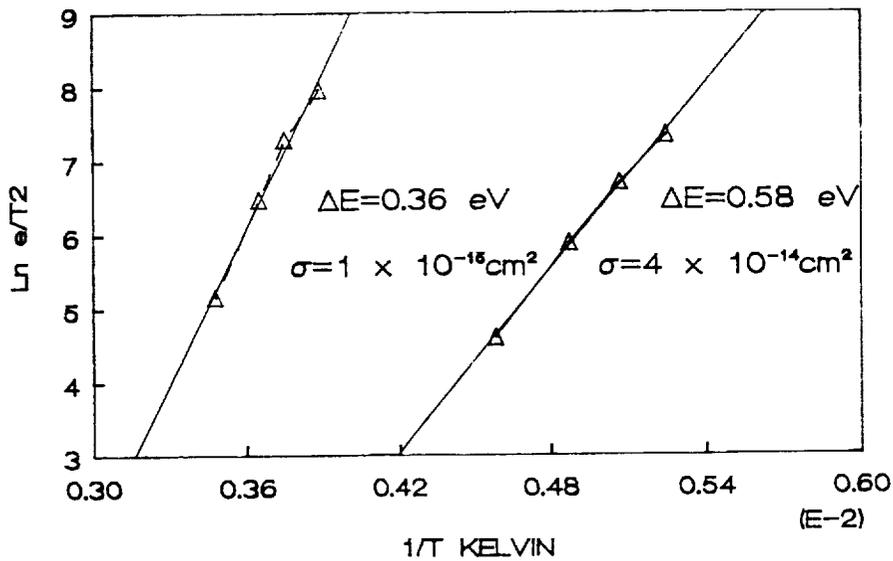
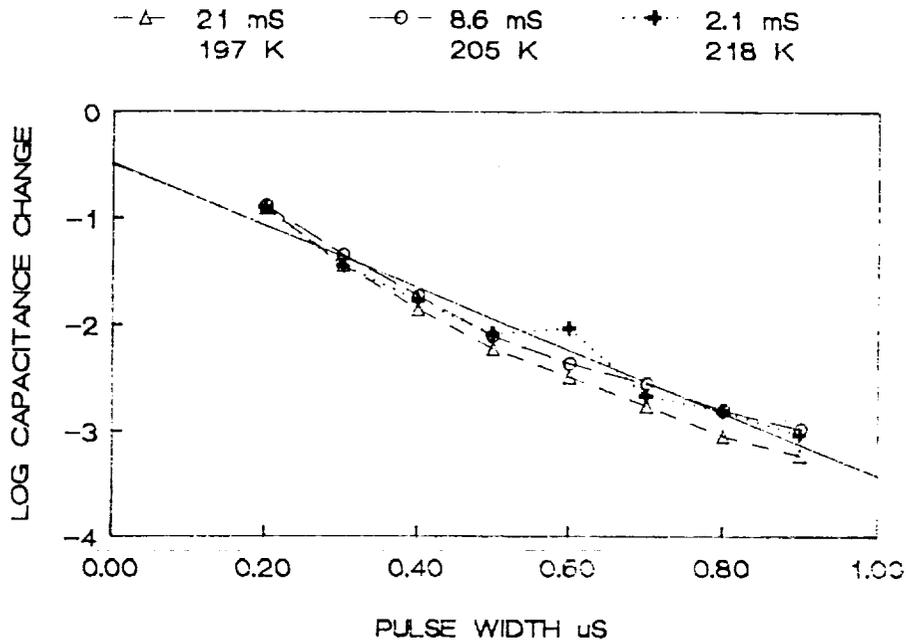


FIGURE 2: DLTS SPECTRUM AND ANALYSIS

CAPTURE CROSS SECTION H4 IN InP



CAPTURE CROSS SECTION H5 IN InP

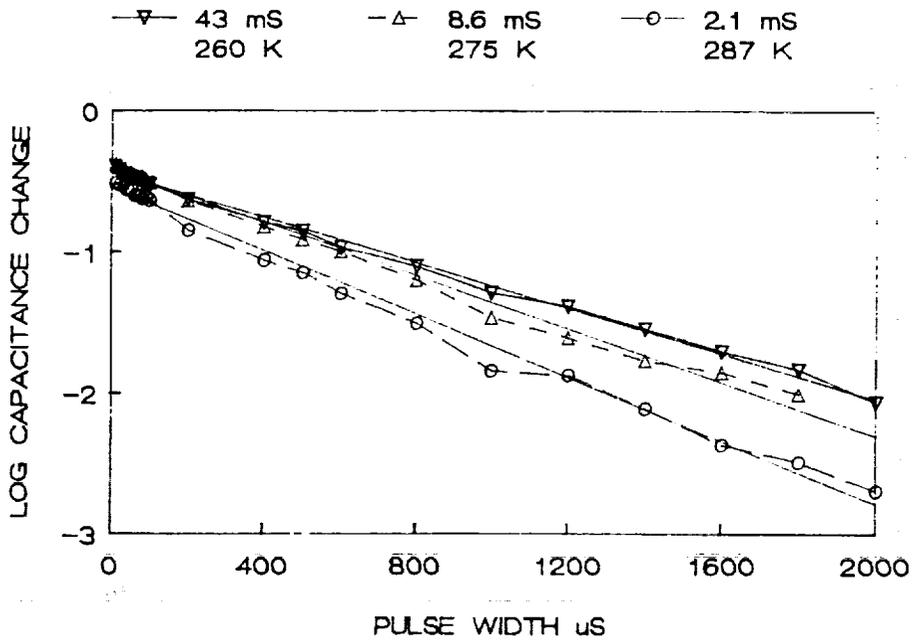


FIGURE 3: CAPTURE CROSS SECTION AND ANALYSIS

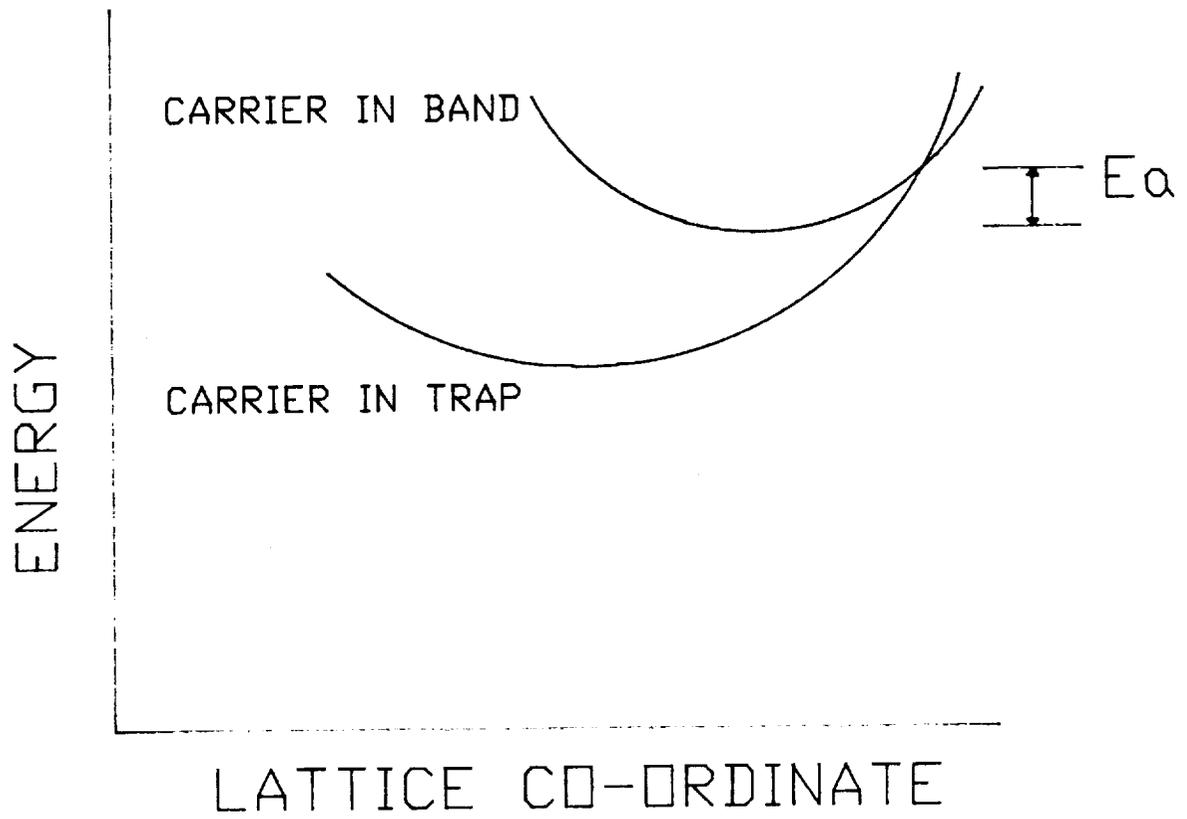


FIGURE 4: SCHEMATIC DIAGRAM OF MPE PROCESS